TUM–HEP–383/00
MPI–PhT/2000-29

A Comparison of the Physics Potential of Future Long Baseline Neutrino Oscillation Experiments*

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Abstract

We compare the generic physics potential of various combinations of conventional Wide Band or Neutrino Factory Beams with different detectors to determine several oscillation parameters in long baseline experiments. For each combination of beam and detector we show the precision which can be obtained for the leading oscillation parameters Δm^2_{31} and $\sin^2 2\theta_{23}$. Furthermore we show the sensitivity to $\sin^2 2\theta_{13}$ and the range in $\sin^2 2\theta_{13}$ for which the sign of Δm^2_{31} can be extracted via matter effects. The results suggest that existing conventional Wide Band Beam and detector technology can be used to considerably improve the precision of neutrino properties until a neutrino factory will be built.

Recent studies of neutrino factories as powerful neutrino sources have shown that precision measurements of neutrino masses and mixings are possible in the future [1]. The development of a neutrino factory includes however challenging technological issues and the development will certainly take some time. It is therefore of interest what can be achieved meanwhile in comparison by using conventional neutrino beams. Such improved conventional experiments will lead to a better knowledge of neutrino parameters, which might be considered as a useful step to simply bridge the time until a neutrino factory will be operating. We will however show in this paper that conventional setups may be able to compete in some aspects with the long baseline neutrino oscillation program of neutrino factories. The results of such intermediate experiments would also be important since they affect the optimal strategies for neutrino factories. This applies especially to the measurement of CP-violation at neutrino factories, where further advance information on the mixing parameters

*Work supported by "Sonderforschungsbereich 375 für Astro-Teilchenphysik" der Deutschen Forschungsgemeinschaft.

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(especially θ_{13}) would be very important [2]. We perform therefore in this paper a global comparison of the generic physics potential of several experimental setups and we present the resulting precision of the leading oscillation parameters (Δm^2_{31} and θ_{23}) as well as the sensitivity to the sub-leading parameters (θ_{13} and the sign of Δm^2_{31}). Our analysis includes energy thresholds and resolutions and we show the dependence on these parameters. Details of the formalism which is used to derive the current results can be found in earlier publications [3, 4, 5].

The experimental setups considered in this study include two different beam types, namely

- conventional Wide Band Beams
- neutrino factory beams

which are assumed to point at three different types of detectors, specifically

- magnetized iron detectors
- large water or ice Cherenkov detectors ("neutrino-telescopes")
- ring imaging water Cherenkov detectors

located at large distance on the surface of the earth. We consider thus very long baselines up to 11200 km and we include therefore the MSW matter effects [6] with the full earth density profile [7]. We study only the detection of muons which are produced by muon neutrinos, since electrons and taus are in general experimentally more difficult. Adding electron and/or tau channels would of course affect the analysis. The generic physics potential of the detectors depends for the considered measurements then in general primarily on three parameters, namely the energy threshold for muon detection, the energy resolution and of course the detector mass. To characterize typical detector concepts via these three parameters is of course a rather simplified approximation of a real detector, but it permits a simple and effective evaluation and comparison of the generic physics potential of very different detector types on a common basis.

The dependence of the analysis on the detector mass is trivial, but important, since it determines the event rates and thus the statistical limitations. The energy thresholds are usually required to lie as low as possible, typically at a few GeV, to cover most of the neutrino beam and to measure the oscillation parameters best. In this paper we approximate that both threshold energy and energy resolution refer to neutrino energies, not muon energies. For the energy resolution we use the conservative model of a constant resolution, where the half width of the smearing function increases linearly with the energy: $\sigma_E = c \times E$. We refer to the constant c here as energy resolution in percent. The results which are obtained in this way show thus the generic physics potential of a certain beam–detector combination including beam properties, cross sections and essential detector features. We do not include systematic limitations and backgrounds which are different for each setup[1]. The results for the generic physics potential, which will be very impressive, are thus in some cases expected to be reduced in the actual experiment by some systematics or background issue.

We discuss now in more detail the assumptions about beams and detectors of our study and the used parameter values. Some of these parameters have simple scaling laws so that other values can be easily obtained. The dependence on the less trivial parameters (like detector

[1]Note however that intrinsic backgrounds due to the beam are very similar for all detectors.

resolution) will be shown in our plots.

The following neutrino beams are considered: Conventional Wide Band Beams are produced by shooting high energy protons with a few hundred GeV onto a massive target [8]. The produced pions and kaons are collected via a magnetic lens system and decay after a few hundred meter. We assume here that these beams can be pointed anywhere on Earth. The resulting beam consists mainly of ν_μ with admixtures of other flavors at the percent level. Reversing the lens current produces in principle a beam consisting mainly of $\bar{\nu}_\mu$, however the systematics of the two beams is different. Examples for this type of neutrino beams are the K2K beam, the NUMI beam and the CNGS beam. We use in our calculations as prototype the CNGS spectrum and flux for $4.5 \cdot 10^{19}$ pot. There exist proposals to upgrade this technique for future long baseline experiments, these improvements can be considered by properly rescaling our results.

Neutrino Factory Beams produced from muon decays in storage rings are highly collimated and very intense.The beam systematics are well understood so that high precision measurements of oscillation parameters and masses, as well as a dedicated test of matter effects, should be possible. We include in this work a Neutrino Factory beam from 10^{20} useful muon decays at an energy of 50 GeV.

Magnetized iron detectors are widely considered to be the detection system of choice for neutrino factory long baseline oscillation experiments [1]. Very good charge identification capabilities (CID) are required to separate muons from antimuons in order to separate the $\nu_e \rightarrow \nu_\mu$ appearance oscillation channel from the $\nu_\mu \rightarrow \nu_\mu$ disappearance channel. If sufficient CID can not be achieved[2], then appearance channel measurements are spoiled and the analysis of the disappearance channels becomes important [4]. To take this issue into account, we consider here the two extreme cases: Perfect CID and completely missing CID. For this type of detector we use an energy threshold of 4 GeV as proposed also in the neutrino factory design studies. Furthermore we use an energy resolution of 10% and a total mass of 10kt [9, 10].

Large water or ice Cherenkov detectors (known also as "neutrino telescopes") [11], which consist of large arrays of photomultipliers (PMTs) placed in antarctic ice or sea water, were until recently not considered for very long baseline neutrino experiments. This is connected to the fact that these detectors are usually thought of as having a rather high energy threshold. This high threshold arises for the reconstruction of cosmic events and is a consequence of the distances in the PMT multiplier arrays and the minimum number of PMT hits for track reconstruction (i.e. the direction of the event). The threshold is also connected to the reduction of the background. It was however recently pointed out, that a neutrino oscillation experiment with high event rate and known source position, can have a much lower threshold [3]. Reconstructing the event direction is in this case in principle not necessary and one can therefore trigger on fewer PMTs leading to a lower threshold for this mode of operation. Using the beam pulse timing information and rough muon direction information it is furthermore possible to reduce the background and hence also the energy threshold significantly. Furthermore we will show in this paper that some measurements are rather insensitive to this threshold. For our study we use as prototype detector IceCube

[2] This issue is still open and one can find claims ranging from 10^{-6} up to 10^{-2}.

with an effective mass of 100Mt and an energy resolution of 50%. The energy threshold should lie somewhere between an optimistic value of 5 GeV and a conservative value of 30 GeV (which could be easily achieved by the IceCube project) and we use in our study a medium value of 15 GeV [3].

As a last type of detector we considered a megaton ring imaging Cherenkov detector like in the AQUA-RICH proposal. Due to its dense optical sensor array and imaging technique, such a detector would have an extraordinary small energy threshold. Furthermore with its 1Mt detector mass, AQUA-RICH lies between the above presented detectors. We use for such a detector as characterizing parameters an energy threshold of 1 GeV, an energy resolution of 7% and an overall mass of 1Mt [12].

	Magnetized Iron Detector	**Water/Ice Cherenkov Detector**	**Megaton Ring Imaging Detector**
Threshold	4 GeV	15 GeV	1 GeV
Resolution	10%	50%	7%
Mass	10 kt	100 Mt	1 Mt
CID	yes	no	no
Examples	MINOS, MONOLITH	AMANDA, IceCube, ANTARES, NESTOR	AQUA-RICH

Table 1: Typical detector parameters.

The results which we will present below are obtained in a standard three neutrino framework in matter. We use for the atmospheric mass splitting the current best fit, i.e. $\Delta m^2_{31} = \Delta m^2_{32} = \Delta m^2 = 3.2 \cdot 10^{-3}$ eV^2 and we use maximal atmospheric mixing, $\sin^2 2\theta_{23} = 1$ [13]. Details of the underlying formalism can again be found in [3, 4, 5]. We work in the limit where the quadratic solar mass splitting is ignored, i.e. $\Delta m^2_{21} = 0$. We have thus two leading oscillation parameters (θ_{23} and Δm^2) and two sub-leading parameters (θ_{13} and $\operatorname{sgn} \Delta m^2$) and no effects from the CP-violating phase δ [2]. This approximation is justified since CP-violating effects disappear quickly for the large distances considered [5]. For the leading oscillation parameters the question is how precise they can be extracted and the goal for the sub-leading parameter θ_{13} is to measure it with some precision or to give at least an improved limit below the present CHOOZ limit of $\sin^2 2\theta_{13} < 0.1$ [14]. θ_{13} also dominantly controls the impact of matter effects in oscillation measurements. Thus the θ_{13} reach is highly correlated with the ability to determine the structure of the mass hierarchy (i.e the sign of Δm^2).

The following plots show the precision in the measurement of these parameters for the three discussed detector types (magnetized iron detector with and without CID, IceCube and AQUA-RICH) in combination with the two beams described. We compare the performance to determine the leading parameters θ_{23} (fig. 1) and $|\Delta m^2_{31}|$ (fig. 2). Also shown is the sensitivity for θ_{13} (fig. 3) and the capability to determine the sign of Δm^2_{31} (fig. 4). Fig. 4 shows the limit in θ_{13} above which tests of matter effects are possible. A detailed explanation of how these results are obtained can be found in [4, 5] where the applied statistical method is also presented. The figures show always on the left side the results for a neutrino factory

beam, while the right plots show the conventional CNGS–like Wide Band Beam.

The precisions and sensitivities in the figures are presented as functions of the energy threshold ranging from 1 GeV to 30 GeV. The dependence on the energy resolution is in all cases strictly monotonic and nearly linear on logarithmic scales. This dependence is shown in the plots by the bands for a resolution of 5% (lower edge) to 50% (upper edge). The black lines inside the bands denote the characteristic energy resolution given above in table 1 and the dot on these lines marks the corresponding typical energy threshold. The baseline of 6500 km may not be a realistic option for IceCube, but the influence of the baseline for detectors without CID is between 6000 km and 12000 km marginal. The sensitivity reach and the resolution scale in general approximately as $\sqrt{M\Phi t}$, where M is the detector mass, Φ the neutrino flux and t the running time of the experiment.

Figs. 1 and 2 show the precision which could in principle be obtained in the determination of $\sin^2 2\theta_{23}$ and $|\Delta m^2_{31}|$ at a baseline of 11200 km. There is no difference in the performance of an iron detector with and without charge identification so that there appears only one band for this type of experiment in the figure. This is not unexpected, since the information on these two parameters is contained in the disappearance rates. All experimental setups show not much influence of the energy threshold on the precision of the leading parameters. The accuracy is mainly governed by statistics which is given essentially by the mass of the detector. Thus IceCube, the largest detector in our study, has for both beams the best potential.

Fig. 3 shows the mean sensitivity to $\sin^2 2\theta_{13}$. The magnetized iron detector benefits here significantly from charge identification (CID), i.e. the capability to measure the appearance channel. For the neutrino factory beam pointing to detectors without CID there is a strong threshold effect at about 15 GeV, which is roughly the MSW–resonance energy in the Earth mantle. This threshold effect is less pronounced for the Wide Band Beam since its flux is much lower in the MSW–resonance energy regime. Fig. 3 demonstrates nicely the importance of the energy threshold for experiments which are based on conventional beams pointing to large Cherenkov detectors like IceCube or ANTARES. Note that neutrino factory beams pointing to large water or ice Cherenkov detectors have in principle the highest potential if the involved technological issues can be solved. A discussion of the questions involved can be found in [3]. The strongest influence of the threshold is found for the determination of the the sign of Δm^2_{31} in fig. 4. For the setups with a neutrino factory beam there is again a clear effect at about 15 GeV, for the same reasons as mentioned above.

In summary, we have compared in this study the generic physics potential for neutrino oscillation studies. We considered neutrino factory beams and conventional Wide Band Beams pointing to three different types of detectors: magnetized iron calorimeters, large water or ice Cherenkov detector and megaton ring imaging Cherenkov detectors. The quantities studied are the precision for the leading oscillation parameters $\sin^2 2\theta_{23}$ and $|\Delta m^2_{31}|$ as well as the sensitivity to the sub-leading MSW–enhanced oscillation parameters $\sin^2 2\theta_{13}$ and the sign of Δm^2_{31}. For the precision measurement of $\sin^2 2\theta_{23}$ and $|\Delta m^2_{31}|$ the single most important parameter which characterizes the performance of a detector is its mass. Neither typical energy thresholds for muon detection nor the energy resolution have a big influence on the precision as long as the threshold does not exceed 30 GeV. Thus large km^3 Cherenkov detectors like IceCube in conjunction with a neutrino factory beam perform in

principle best, with a relative error down to about $4 \cdot 10^{-4}$. A conventional beam pointed to an IceCube-like detector performs in principle about half an order of magnitude better than the usually considered combination of neutrino factory and magnetized iron calorimeter, which has an error of about 10^{-2}. Note however that we discuss here the generic physics potential which can be achieved in principle and further systematic and background effects may (and probably will) affect our conclusions.

For the determination of the sub-leading parameters $\sin^2 2\theta_{13}$ and the sign of Δm^2_{31} we find a different situation in our results. The possibility to measure appearance rates (requiring sufficient muon charge identification) is here extremely helpful. Especially for detectors without charge identification we observe an intricate interplay of event rates, threshold and energy resolution. To obtain useful results with a conventional beam one needs then very large detector masses of at least 1 Mt. The threshold dependence of the limits is also rather strong and the energy resolution is also important. Huge IceCube-like detectors and the megaton ring imaging detector (AQUA-RICH) have however in principle a comparable performance down to $\sin^2 2\theta_{13} \simeq (2-8) \cdot 10^{-3}$. The wrong sign muon signal in a magnetized iron calorimeter gives for a neutrino factory beam the best sensitivity of about $\sin^2 2\theta_{13} \simeq 10^{-4}$. The performance of IceCube is however in principle rather similar and reaches also down to $\sin^2 2\theta_{13} \simeq 4 \cdot 10^{-4}$. Note however again that we study here the generic physics potential and the measurement of $\sin^2 2\theta_{13}$ and the sign of Δm^2_{31} will be limited essentially in all cases by further systematic and background issues.

Our results show in a larger context that detectors with imperfect or even missing muon charge identification (which are therefore insensitive to the appearance oscillation channel) are useful for precision measurements of oscillation parameters [3]. Especially in high rate neutrino experiments, where statistical errors are small, the information which is inherent to the disappearance rates is very useful.

The generic physics potential studied here is expected to be at least in some cases limited by further technological limitations, systematic and background effects. For magnetized iron detectors excellent charge separation is for example a crucial issue. Neutrino telescopes are in principle very interesting due to their huge mass. For the high event rates obtained directional information becomes less important and it is possible to lower the threshold and to use them for oscillation physics. How well this works has to be further studied. For Wide Band Beams the limiting factors could e.g. lie in the flux monitoring with a near detector. On the other side Wide Band Beam technology will improve even further.

Altogether Wide Band Beams have in principle a very good physics potential to improve our knowledge of $\sin^2 2\theta_{23}$, $|\Delta m^2_{31}|$, $\sin^2 2\theta_{13}$ and the sign of Δm^2_{31} until a neutrino factory is built. It is thus conceivable that $\sin^2 2\theta_{13}$ and even the sign of Δm^2_{31} could be measured (or limited) with conventional beams even down to $\sin^2 2\theta_{13} \simeq 10^{-3}$. A neutrino factory would enable measurements (or limits) of these parameters down to $\sin^2 2\theta_{13} \simeq 10^{-4}$ and in addition it would so far be the only realistic way to measure leptonic CP–violation [2].

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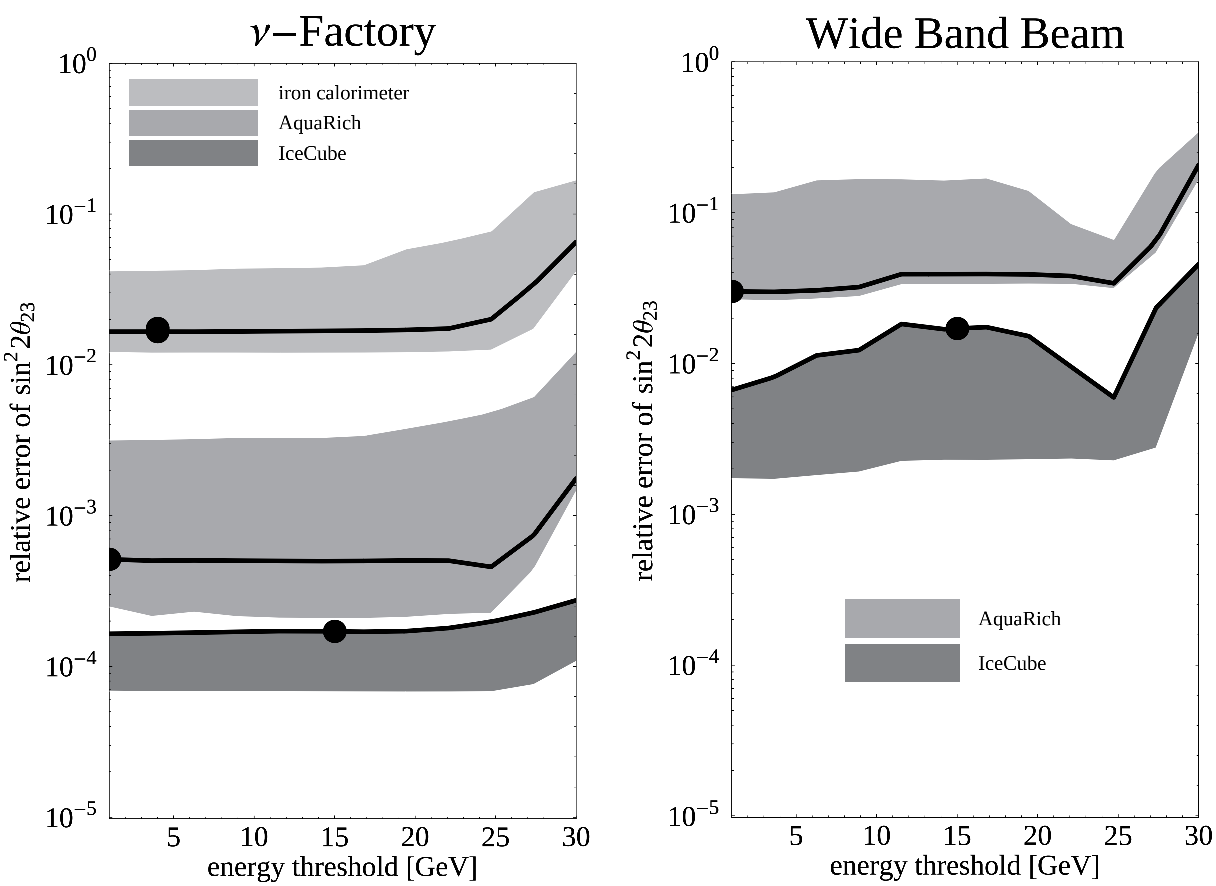

Figure 1: *Relative 3σ–errors of* $\sin^2 2\theta_{23}$ *as a function of the energy threshold of the detector at a baseline of 11200 km. The colored bands show the influence of the energy resolution from 5% (lower edge) up to 50% (upper edge). The black lines indicate the energy resolution of a typical detector of the corresponding type and the black dots mark the typical threshold value on this line as specified in table 1.*

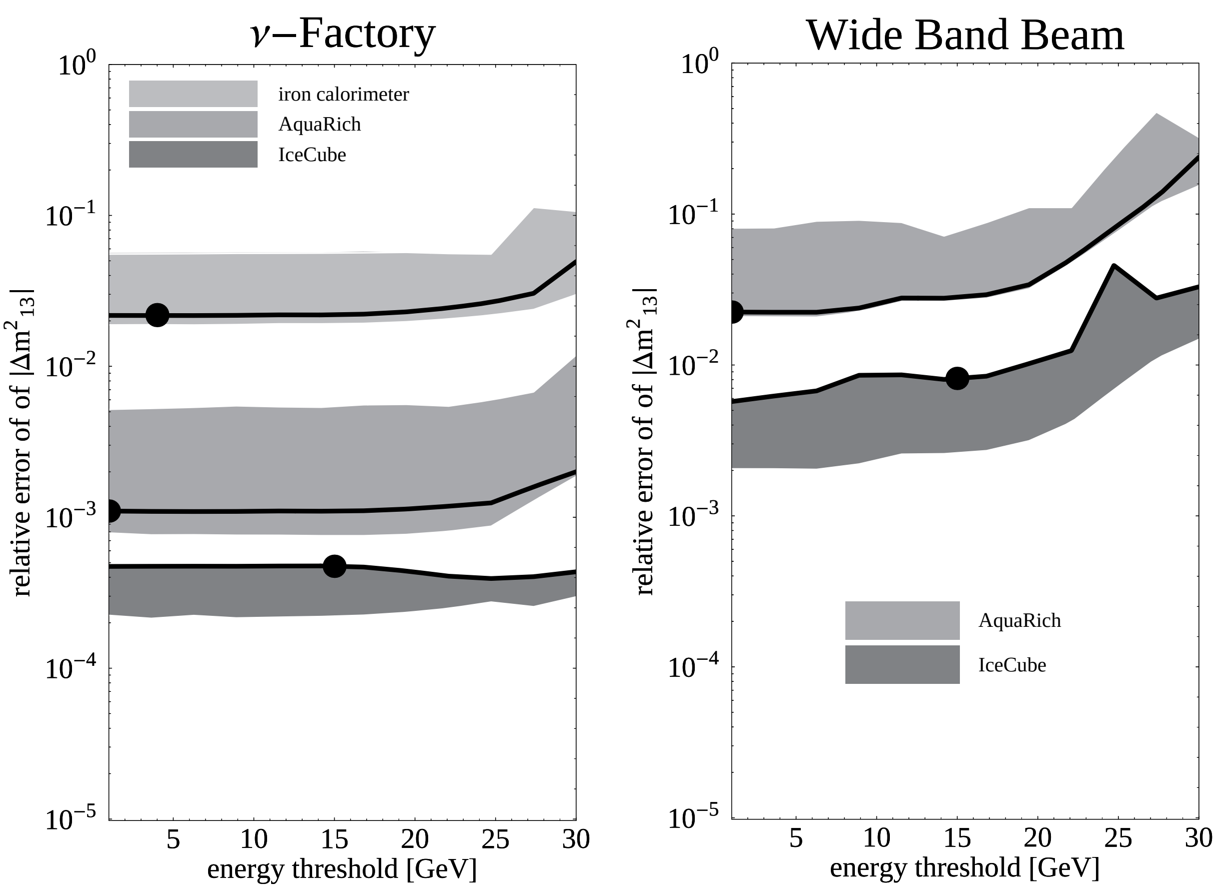

Figure 2: *Relative 3σ–error in* $|\Delta m^2_{31}|$ *as a function of the energy threshold of the detector at a baseline of 11200 km. The colored bands show the influence of the energy resolution from 5% (lower edge) up to 50% (upper edge). The black lines indicate the energy resolution of a typical detector of the corresponding type and the black dots mark the typical threshold value on this line as specified in table 1.*

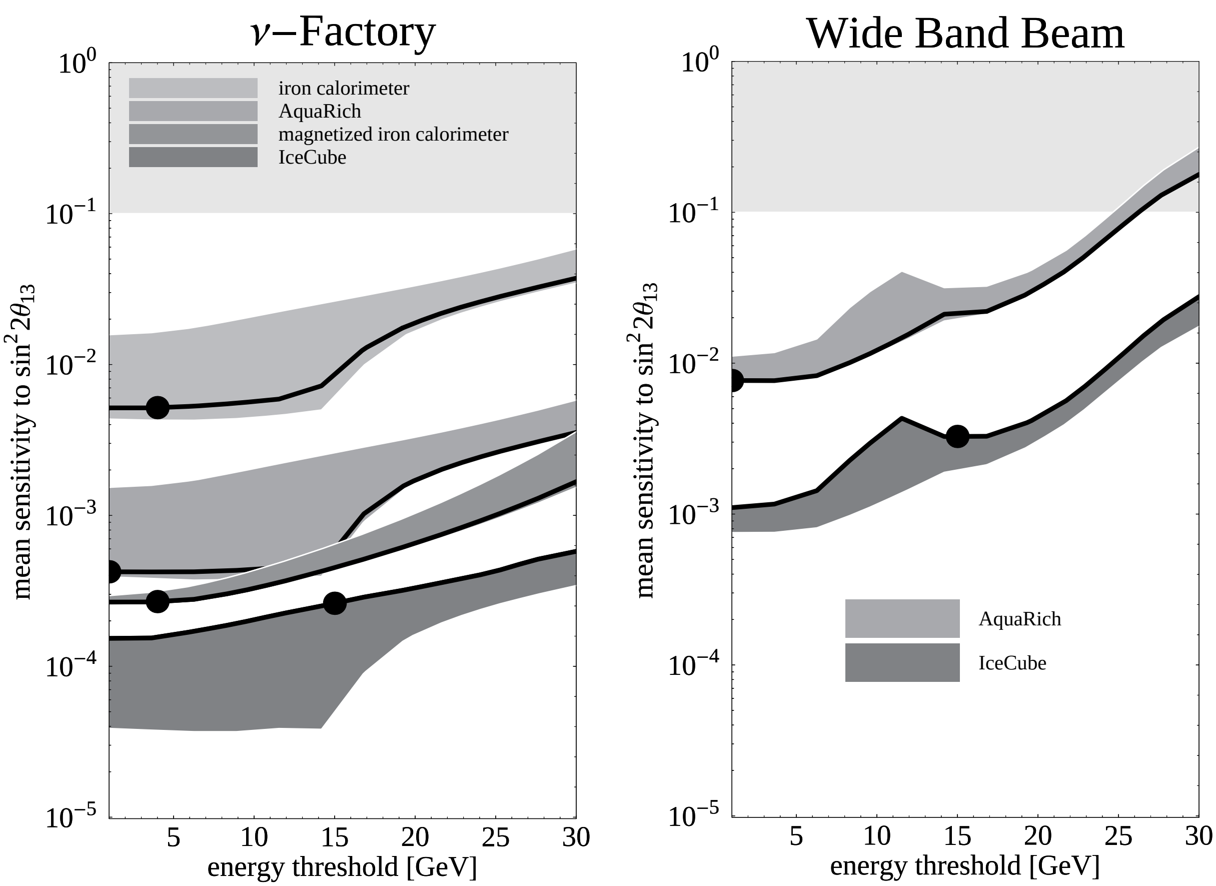

Figure 3: *Mean sensitivity at 90% C.L. to* $\sin^2 2\theta_{13}$ *depending on the energy threshold of the detector at a baseline of 6500 km. The colored bands show the influence of the energy resolution from 5% (lower edge) up to 50% (upper edge). The black lines indicate the energy resolution of a typical detector of the corresponding type and the black dots mark the typical threshold value on this line as specified in table 1. The light grey shaded area represents the CHOOZ limit.*

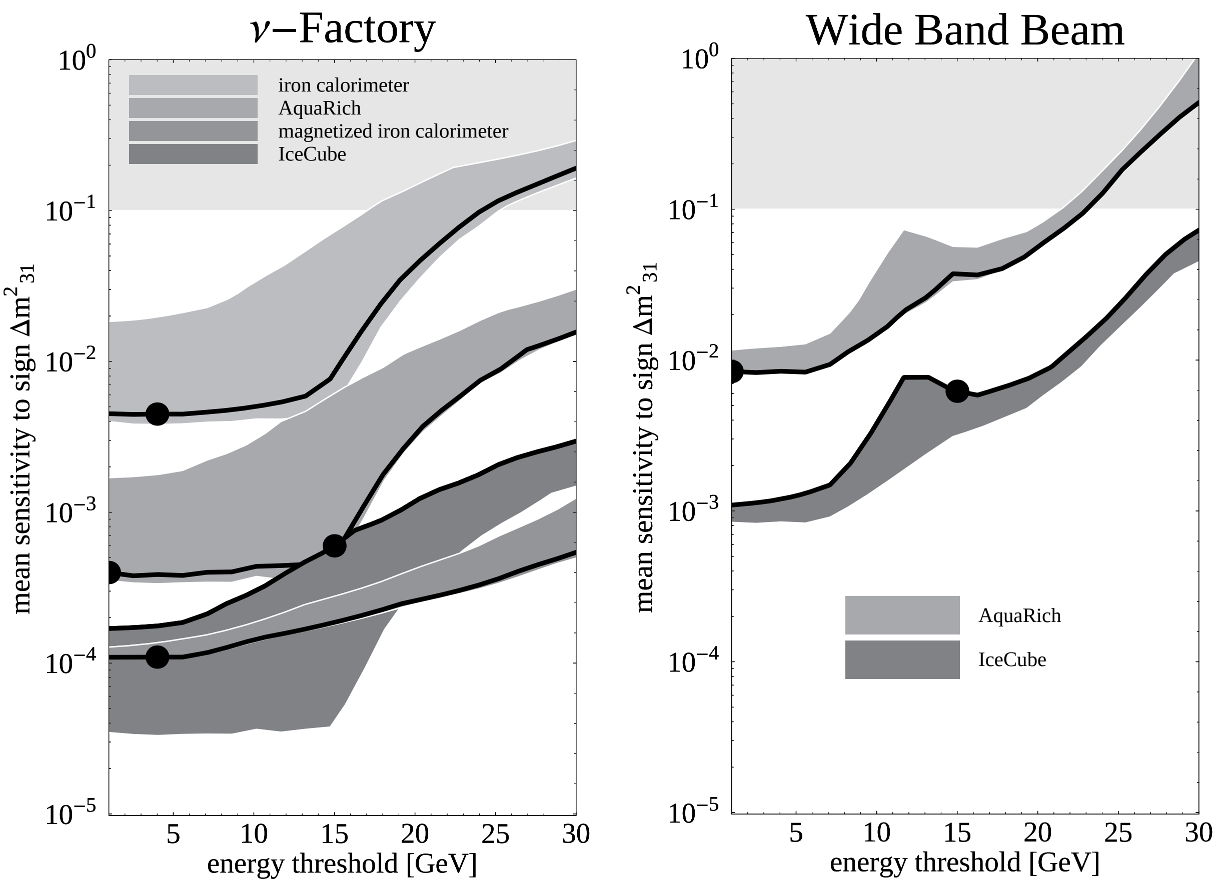

Figure 4: *Mean sensitivity in* $\sin^2 2\theta_{13}$ *at 90% C.L. to the sign of* Δm^2_{31} *depending on energy threshold of the detector at a baseline of 6500 km. The colored bands show the influence of the energy resolution from 5% (lower edge) up to 50% (upper edge). The black lines indicate the energy resolution of a typical detector of the corresponding type and the black dots mark the typical threshold value on this line as specified in table 1. The light grey shaded area represents the CHOOZ limit.*